Low Cost Ground Systems - Fantasy or Reality[1]

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Abstract – During the concept phase and initial design of a NASA spacecraft, no NASA project says, 'I want an expensive ground system'. In fact, as with other parts of the total project, a zero cost option is the preferred choice. Our experience has shown that putting together a 'low cost' ground system including development systems, control center and ground station, is not as simple as one is first lead to believe.

This paper will address several areas of ground system design: onboard spacecraft, ground stations and networks, simulators and laboratories, Telemetry and Command Systems, all of which require careful analysis to accommodate the ground systems cost savings.

We have also found that changes to the ground system design are often used to reduce technical risk in other areas of the mission. Many of the ground system impacts from these changes are advertised as 'low cost', but when taken

as a whole, the cost impact on the ground system can be large.

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1. INTRODUCTION

As cost becomes more of a concern within NASA, the goal for low cost operations is becoming more of a driver than in the past. The idea is that low cost operations will allow a larger part of the projects budget to be spent on the spacecraft and science. This paper is the result of experience gained from the ground system development for the Nexus mission, and subsequent concept development for the Next Generation Space Telescope (NGST) mission.

The Nexus mission was planned as a technology demonstrator project for NGST, with a launch in 2005. Nexus was scheduled to be a short-duration mission requiring ground systems with minimal cost and minimal development risk. Nexus was intended to be a smaller scale telescope than NGST, designed to test telescope deployment and optical stability, the on-orbit Wave Front Sensing and Control process, and sunshield thermal performance. Goddard Space Flight Center (GSFC) and the Space Telescope Science Institute (STScI) jointly developed the Nexus ground system. Due to a re-scope of NGST and growth in Nexus total cost, Nexus was cancelled in December 2000.

NGST is a large aperture space telescope designated to succeed the Hubble Space Telescope (HST), as part of the NASA Great Observatories program. NGST will continue the HST tradition of advancing breakthroughs in our understanding of the origins of the earliest stars, galaxies, and very elements that are the foundations of Life. We expect the costs for NGST to be substantially less than from those for HST since NGST will not require Shuttle Mission servicing (it will maintain an orbit around L2, the second Lagrange point). HST is very unique in being a serviceable spacecraft, but this also added to the overall ground system cost due to the extended life of the spacecraft and changes to the instrument complement every few years. Our goal for the NGST ground segment is to reduce the cost to between 50% and 75% compared to HST. NGST will accomplish some of this cost saving with reduced contact time, enhancements in guaranteed data delivery protocols, advancements in spacecraft command and control, as well as, reducing the need for manpower for normal operations. NGST is a long-duration mission in the NASA Great Observatory program, but many of the concepts and analyses from the Nexus effort are directly applicable to NGST.

The Nexus ground system team's first task was to determine the true cost and scope of all the systems to support the spacecraft. Figure 1 shows the scope of the overall systems and their connectivity. The evaluation, costing and trade studies for Nexus included costs for:

- Ground Systems,
- Ground Stations,
- Spacecraft Communication,
- Simulators,
- Various Laboratories, and
- Data lines and Networks.

The team also participated in cost trades of additional or changes in the spacecraft communications systems to accommodate an overall lower cost.

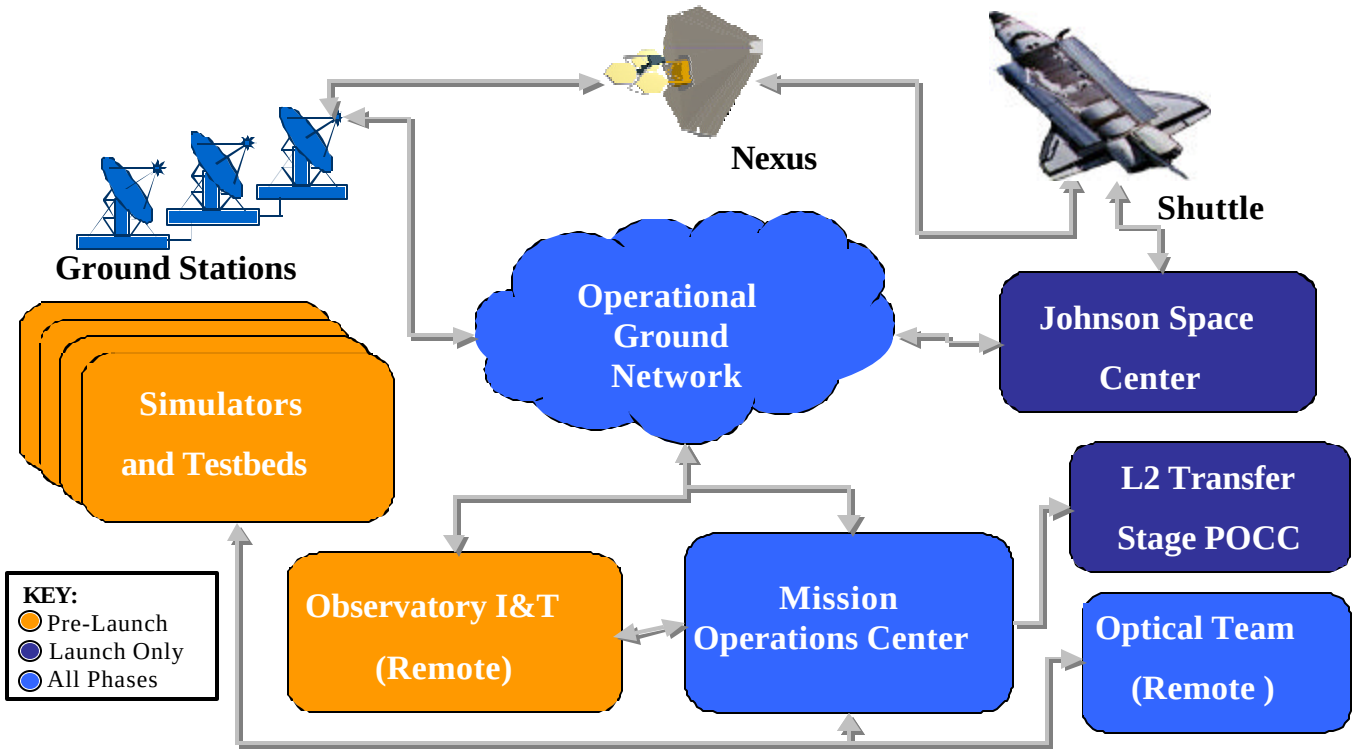

Figure 1 – Ground System Team Scope

The ground system team completed most of the costing and selection activities before the spacecraft project was cancelled. The cancellation was in part due to higher than anticipated costs. The overall breakdown of ground system costs is shown in Figure 2. A similar categorization of ground systems costs can serve to guide cost trades. Note that the real-time telemetry and command system costs are small when compared to the entire system. The Nexus ground system team applied considerable energies to the real-time telemetry and command system trades which might have been better applied to the ground station or simulators and laboratory trades for to realize a greater total savings.

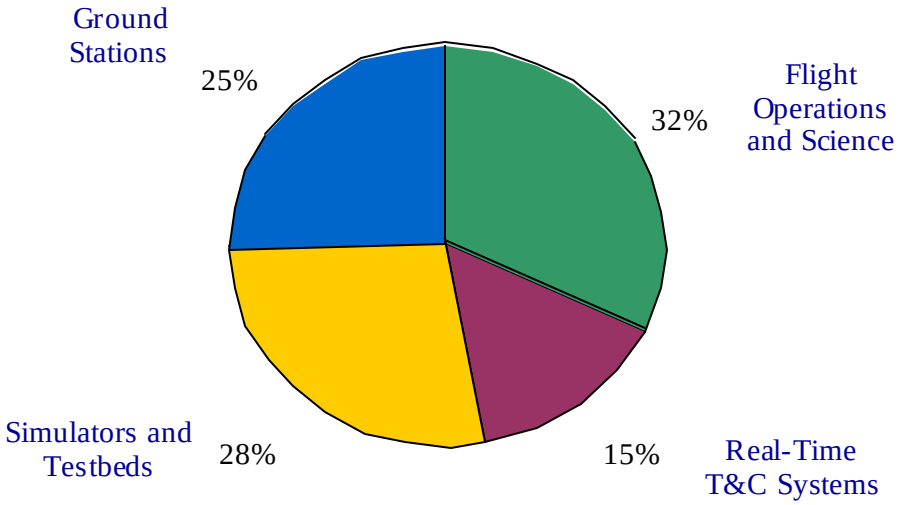

Figure 2 – Ground System Costs

2. THE ISSUE

The program level requirements, for example automation of the ground system, often conflicted with the objectives of low cost development, ground system, and operations

The Nexus mission originally had the ground system goals, as many NASA programs, of a low technical risk, low development cost and low operations cost system. The Nexus requirement for ground system automation did not result in significant savings. At the program level of Nexus, contact time cost greatly exceeded the potential cost savings between automation development and cost of off-shift operations personnel. The cost trades and requirement evaluations should have focused on the contact time and the savings at the ground stations.

The ground system team evaluated many different approaches to meet the challenges of the Nexus mission design and impact of such approaches on the ground system, operations, and spacecraft. To accomplish this the ground system team conducted the following trade-offs to reduce cost:

- Novel approaches to the space and ground link to reduce ground system costs that were rejected by Nexus project to minimize technical risk.
- Ground stations costs: Commercial versus Government and leasing versus owning.
- Tradeoffs of contact time verses operational risk during the commissioning phase.
- Ground transport of the data via various Wide Area Network (WAN) and international WAN alternatives.
- Prioritizing ground transport of data to reduce the total peak bandwidth.
- The need for a multiplicity of simulators, laboratories and supporting ground systems.
- The number of separate facilities and the testing done in each facility to minimize test duplication and maximize the testing value per dollar spent
- Spacecraft and operational changes in the telemetry and command data rates, protocols, and system designs.

One approach to bring down the total cost of the system is to trade off contact time, data rates and data volume. Data rate and spacecraft antenna size traded against longer contact times and use of smaller, less expensive ground station antennas. Reducing the data rate without dramatically increasing the contact time traded against the increased spacecraft complexity to reduce the volume of telemetry data. The above trades were not completed before the Nexus project was terminated. Additionally, the concepts to reduce the volume of telemetry including downlinking change only data, data compressions, and use of reliable data transfer protocols had yet to be explored.

A 'low cost' ground system can only be achieved as an integral part of the mission solution. Total ground system costs are tightly coupled to the spacecraft and mission design. The Nexus spacecraft reduced the ground station costs by 50% by putting a larger antenna on the spacecraft, which allowed for use of a smaller antenna at the ground station.

The Nexus initial launch and commissioning support requirements was initially 24 by 7 contact for one hundred days. The cost of the contact time to meet this requirement dwarfed the remaining ground system costs. This requirement was subsequently relaxed after the desire for the early telemetry was measured against its cost. The Nexus Project revised the requirement to better balance ground system costs against the risk of early spacecraft problems. We found that Science Instrument teams often requested large volumes of data which portions are unlikely to ever to be used. Onboard analysis of the science data and downlinking only the relevant data, and not all the data, can decrease the overall cost of the ground systems, at the risk missing or losing science data that was not recognized at the time as pertinent.

3. GROUND STATIONS AND NETWORKS

NASA has decided to move away from operating ground stations and toward using commercial ground stations. NASA did this hoping that commercial carriers would reduce the cost of ground stations. Overall, since NASA is currently not supplying the space-to-ground link infrastructure, it is no longer a cost item for missions provided out of a central shared fund.

Dedicated ground stations for a single spacecraft are often not worth the cost for a short-term mission. From an end user perspective the commercial sites can offer a competitive cost if the spacecraft design, dedicated contact requirements, and downlink rates are considered as a risk verses benefit, including cost, early in the development cycle.

The ground station costs can be divided into three segments:

1. Contact time and associated costs
2. Cost of transporting data between the ground stations and control center
3. Cost savings via ground automation, reducing the number and skills needed at a ground station

The cost of the ground network between the ground stations and the control center was underestimated during the preliminary mission design phase for Nexus. The cost of the network between the various labs and spacecraft Integration & Test (I&T) facilities was not in any of the early budget calculations. In the NASA era of full cost accounting for all services, these network costs will "nickel and dime" a project to death. The cost of cables, routers, hubs, switches, redundancy, and personnel to support the

network are not a one-time cost and often are overlooked.

To reduce the transmission cost from the ground stations to the control center, the Nexus concept was to decode science data at the ground site before transmission to the control center. This reduced the total bandwidth needed. Also, the use of CCSDS virtual channel assignments allowed Nexus to only transmit critical data in real-time to the control center. Remaining data would be transmitted as bandwidth became available.

One item, which was left unexplored, was to use the existing open Internet to transmit the spacecraft data. Using the open Internet has many advantages in trying to meet the low cost objectives. Encryption, digital signatures, and other data security measures can be used to protect proprietary data. One of the disadvantages is the lack of guaranteed data bandwidth performance, which must be accommodated for in the total system design.

Automation of the Nexus control center required a longer mission lifetime or cost sharing across multiple programs to be affordable. Automation to collect and store telemetry at the ground station would have been more cost effective by benefiting multiple ground station users, to share the cost of development and implementation, and to support personnel reductions or unattended operations within the Nexus control center.

The 'big' costs in the total ground system are the costs of the ground station time and resources and the network to transport the high volume data. The Nexus project should have focused on evaluating and exploring ways of reducing these costs instead of real-time telemetry and command systems and ground system automation.

4. SIMULATIONS AND LABORATORIES

In general, the number of laboratories grew very quickly on Nexus to a total of fourteen. It is not just expensive in facilities, material, maintenance, logistics and labor, but this diversity can discourage collaboration, lead to duplicated testing and low return on the cost of testing. This unexpected cost of supporting multiple laboratories, which was much more than originally estimated, helped push the total ground system cost over it's planned budget.

The project must control the levels of testing to control the number and cost of the various simulations systems required during spacecraft development and testing. Uncontrolled testing of requirements can balloon the simulator costs by requiring overly sophisticated and high fidelity simulators.

A consolidated approach and management for simulators and laboratories from the beginning of the project will reduce the overlaps, mixed requirements, and need for multiple systems. When added together the total cost for simulators and laboratories was higher than the total real-time Telemetry and Command (T&C) systems. The T&C ground system costs included the flight operations hardware, development, enhancements, and software. Another challenge for the concept of a low cost ground system, is the total number of ground systems to be purchased and maintained. With computer hardware and interface card costs decreasing, and available bandwidth increasing, most organizations are now asking for a dedicated ground system. On the Nexus project, the three ground systems to be used for operations paled against the fourteen ground systems needed for the various Integration and Test, Flight Software development, science instrument and spacecraft builder facilities.

The development and testing of the Nexus spacecraft required the coordinated efforts of a large number of engineers working in a number of facilities. As the spacecraft schedule was developed, the ground system team was surprised to count fourteen separate facilities that required a real-time T&C ground system. Additional integration and environmental test facilities were identified that required real-time T&C ground systems but could re-use systems which had already been procured for other facilities. This distributed approach to development and testing made the number of test facilities, and the resulting number of real-time T&C ground systems they required, an important cost issue. The overall cost to procure the real-time T&C ground systems was dominated by the number of facilities receiving such systems, rather than the relative cost of each instance of each system. The total cost to procure the systems to support I&T was far larger than the cost to procure the systems to support flight operations.

The proliferation of separate testing facilities confers some benefits in making the mission schedule less dependent on critical hardware or facilities. Additional facilities can also increase costs due to the need for additional simulations and test equipment and the potential for unnecessary test duplication, as well as the facility costs. Fewer shared testing facilities would reduce ground system procurement costs. Shared testing facilities also have the potential to encourage increased collaboration among spacecraft developers.

A major cost issue for testing facilities is represented by the simulators needed to adequately test spacecraft components before launch. The ground system team found that the fidelity of simulators could be addressed in terms of cost versus simulator fidelity, but the tradeoff between simulator fidelity and program level risk was poorly understood.

5. TELEMETRY AND COMMAND

Most satellites, including Nexus, have been slow to adopt new ways of implementing the telemetry and command systems between the ground and spacecraft. Innovation in

the real-time ground system software and hardware, which can achieve great cost saving, has been lacking in the last several years. Most of the current commercial systems that were reviewed are providing pieces of the system and spacecraft users select and integrate the pieces needs to form a total ground system. The heritage of the spacecraft bus can be the most important discriminator in selecting the telemetry and command system because of the legacy of proven operations and protocols.

The Nexus spacecraft used a traditional GSFC model for a spacecraft flight software development. It was, and is still by some, thought to be the most cost effective way to develop and operate the spacecraft. The ground system team, in order to reduce long term cost, approached several ways to reduce uplink and downlink data volumes by changing what the ground does verses what is done onboard the spacecraft.

On Nexus there were two transmission frequencies, S-band and X-band. The S-band was initially designed for command uplink and health and safety downlink. The X-band system was for high rate data dumps from the onboard, solid state recorders.

On the uplink side of the interface, to reduce the amount of uplink time and rate needed, the goal was to limit the amount of uplink commands by using key macros execution, onboard scheduling, branching of tasks, autonomous orbit determination, and onboard use higher level products. Instead of depending on telemetry verification of command receipt, the CCSDS/CFDP protocol could be used to reduce retransmission times.

Most of the potential cost savings are on the downlink side of the interface, since this is a much larger quantity of data than the uplink portion of the interface. Onboard the spacecraft the exploration of ideas for packaging the data, change only data, and onboard processing of science data to delete non-useful data were discussed but not implemented due to the Nexus short timeframe between development and launch.

6. SUMMARY

There can be no “low cost” control center without a basis to judge low cost. The ground segment is only one piece of the entire satellite project puzzle and its importance is not equal to that of the spacecraft. However, a small changes on the spacecraft, such as increasing the spacecraft antenna size, can save many dollars farther down the road in ground system, data transfer or operations costs.

Throughout a project several trades need to be done; Ground cost versus spacecraft cost, data guarantee versus data loss risk, and down-linking all data versus putting more logic for science processing on board. One option, used on many spacecrafts today, is to increase the spacecraft recorder size to space the downlink periods farther apart and reduce the amount of ground station contact time. Recording telemetry data at the ground station for processing reduced rate playback later at the control center provides flexibility in addressing ground to ground data transport costs and ground system staffing schedules.

There are many examples of additional cost and design trades that can be done: dual transmitters at different frequencies for simultaneous down-links, guaranteed data delivery protocol or error correction schemes, down-link change only data, and others.

Satellites with short mission duration could benefit greatly if NASA supplied the space-to-ground link infrastructure to its own and other United States Government missions. The cost sharing of the facility, hardware, and personnel across multiple spacecrafts will be more easily coordinated. It is our finding that the objectives of low cost missions that include ground segments cannot be met without this support.

The ground system team experience has been that most benefit for the dollar can be in examining the true requirements and needs, rather than historical operations or desirements, early in the design phase and often the savings is in basic communications, not in the fancy buzz words at that time.

7. REFERENCES

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8. BIOGRAPHIES

Jonathan Gal-Edd has been working at NASA since 1994. His current assignment is the Ground Systems Lead for the Next Generation Space Telescope (NGST). NGST is the follow on program to the Hubble Space Telescope (HST)

and is now entering the design and development phase (Phase B). Jonathan was also the Ground System Manager for the NGST flight demonstrator called Nexus. Previous to these missions, Jonathan was a member of the GSFC development team for Earth Observing Science (EOS) information system (DIS). Prior to moving to GSFC from Johnson Space Center (JSC), Jonathan served as the Software Development and Integration Lab (SDIL) Manager, for the International Space Station (ISS) program.

Jane Steck has supported NASA missions since 1971 as a Data Analyst, Programmer, Consultant, Control Center System Manger, Group Lead and Ground System Engineer. NASA Missions she has supported include ACE, EUVE, HST, Nexus, NGST, XTE and is currently involved in the architecture for a new GSFC initiative (GMSEC) to support future GSFC "low-cost ground system" missions including constellations. Jane contributed to the successful design, development, and launch of the ACE mission, which was provided substantially under budget and was the first GSFC mission to adopt an "end-to-end" common ground system approach. Jane has also supported NASCOM, and Science Data Products. She has received several NASA Public Service awards, Special Act awards, and Customer Service Excellence awards for her contributions to these missions. Jane received a B.S. in mathematics/physics/computer science from the University of Maryland in 1971.

Curtis Fatig is the lead Hubble Space Telescope Servicing Mission Test and Integration Engineer. His team of engineers set up remote Payload Operations Centers, test the entire ground and space software and communication links used for each HST servicing mission, and test NASA institutional upgrades affecting HST. He also supports long term development of new mission ground systems. He received NASA's Spaceflight Awareness Award, Public Service Medal, and many Achievement Awards for these efforts from GSFC, KSC and JSC. He received a B.S. from Salisbury State College in 1978 and a M.Ed. from Rollins College in 1982.

Robert Zepp has been developing spacecraft ground systems since 1993, including work on the RXTE, TRMM, CGRO, EUVE, ACE and Landsat 7 ground systems. Rob received a B.S. in Electrical Engineering from the State University of New York at Buffalo in 1981.